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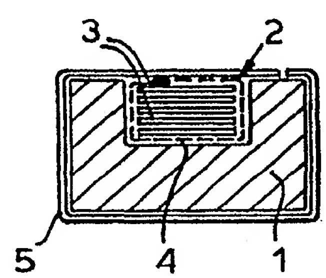
(54) Title: ELECTRIC CONDUCTORS AND CABLES

(57) Abstract

A conductor for a superconducting cable comprises a hollow copper section, either open (a channel) or closed (a tube) having at least one elementary superconductor tape loosely housed within it so as to admit relative movement with respect to the copper section, at least (and preferably only, once the conductor is terminated) in the direction of the width of the tape(s). This provides adequate contact between the tape(s) and the copper without giving rise to the stresses and risk of damage on flexing a conductor in which the tapes are solidly bonded to the copper.



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Electric Conductors and Cables

This invention relates to electric conductors for use in cables and more particularly in power cables with conductors comprising material that is superconducting at the operating temperature of the cable, hereinafter for brevity called "superconducting cables". It relates primarily to superconducting conductors for cables comprising "high temperature" ceramic superconducting materials with an operating temperature over 15K. It also includes the cables in which such conductors are used.

To achieve adequate supercurrent capacity in such conductors, it is necessary to form them from a plurality of elementary superconductors, normally in the form of flat tapes and typically comprising a flattened tube of silver containing particles of the superconducting ceramic which are anisotropic and should as far as practicable be aligned with their major faces parallel to the flat surfaces of the tape. Such tapes will normally be associated with carriers of copper, primarily to provide structural support and an alternative current path of reasonably low resistance in the event of a small portion of the superconductor losing its superconducting character owing to localised high temperature or magnetic field (or to other causes).

Hitherto it has been the normal practice to bond the elementary superconductor tapes solidly to the copper carriers by brazing or soldering, which not only incurs manufacturing costs but also produces a composite conductor which is relatively stiff and risks damage on flexing.

We have now discovered that it is not necessary to maintain contact between the tapes and the copper carrier at every point along their length and that a robust and

effective conductor can be made without any solid bonding between the tapes and the carrier.

In accordance with the invention, a conductor for a superconducting cable comprises a hollow copper section having at least one elementary superconductor tape loosely housed within it so as to admit relative movement with respect to the copper section at least in the direction of the width of the tape.

To maximise contact between the tape and the copper section, and between one tape and another when there is more than one, we prefer that substantial relative movement is permitted only in that direction when the conductor is terminated, but some freedom of movement in the directions of the thickness and/or the length of the tape(s) is not excluded and freedom of movement in the direction of the length of the tape is desirable during assembly of the conductor into a cable.

Localised bonding of the tape(s) to the copper section is not excluded provided that the required movement is available for a large proportion of its length; but it is not recommended, except where external connections are being made.

The hollow copper section may be a closed one (a tube) or an open one (a channel) but should preferably extend around at least three sides of the tape(s). If it is initially an open section, it may be wholly or partly closed either by changing its shape or by adding a separate closure member after assembly with the tape(s). The copper section preferably has at least one flat internal surface presented to one of the flat faces of the (or a) tape to provide opportunity for face-to-face contact.

For maximum effectiveness, the section and any separate closure member is preferably made entirely of copper, but the inclusion of other materials (such as stainless steel for mechanical support or tin to facilitate soldering if and where required) is permitted, and in some cases a closure member might be wholly non-conducting.

Cooling requirements limit the cross-section that is acceptable, and for use in cable of practical capacity it will normally be necessary to assemble together several of the conductors described. Preferably they are externally of a shape (or shapes) that can be assembled, longitudinally or preferably with a helical lay, to form a tubular overall conductor, with or without using a separate cylindrical internal support. For use with a support, the copper sections may be trapezoidal or segments of a cylinder (or if the number to be asembled is sufficiently large, may be square or rectangular). For use without a support, these simple shapes are preferably modified to provide interlocking formations on the contiguous surfaces of adjacent copper segments: for instance, one face of each section may be formed with a projection and its opposite face with a corresponding groove, or (if the number of sections to be assembled is even) half the copper sections may have projections and the other half grooves on both the faces that will be contiguous with the other type of section when assembled.

Any of the several known ceramic superconductor materials may be used; at present we prefer to use "BSCCO" superconductors of empirical formula $Bi_{2-x}Pb_xSr_2Ca_2Cu_3O_{10-\delta}$ (where δ is less than 1) but this is rather on grounds of better availability than of particular technical merit. The

invention might be used with elementary superconductor tapes of metallic material (e.g. of Nb_3Sn).

When using ceramic superconducting materials, we prefer to form them into tapes by a "powder-in-tube" process in which a silver tube is packed with the superconducting material (or a precursor that can be rendered superconducting by subsequent heat-treatment) and the tube then converted to a tape of much smaller cross-section by a process comprising at least one of drawing, swaging, rolling (longitudinal or transverse), rotary forging, or progressive pressing. The last three processes, and more particularly rolling and rotary forging, are preferred as they offer a higher degree of particle alignment than drawing or swaging.

With current superconductor tape technology, the number of elementary superconductor tapes inserted in a carrier is likely to be in the approximate range 5-20. If the copper section is open, and the properties of the available tapes vary (as is the case with current pilot production superconducting tapes) it is preferable to select tapes with the highest critical current densities (J_c values) for location closest to the base of the copper section, since tapes in this position may carry a disproportionate share of surge currents on the occurrence of faults or switching.

Preferably the tapes are pre-assembled into one or more than one bundle to simplify insertion into the copper section; such bundles may be secured by a closed or open wrapping of thin flexible copper (or silver) tape or by an open wrapping of a suitable plastics material.

The cable in accordance with the invention includes at least two conductors as described and means for insulating them electrically from each other and thermally from the

environment (and will be associated in an installation with means for cooling at least the conductors to a cryogenic working temperature). Preferably at least two overall tubular conductors of the kind described are concentrically arranged around a central coolant duct.

Preferred electrical insulating materials are paper (broadly following the practice of oil-impregnated paper power cables, but with an insulating gas (or liquified gas) and not oil as impregnant. The same insulating gas (or liquified gas) may also serve as coolant.

The invention will be further described, by way of example, with reference to the accompanying drawings in which:

Each of Figures 1-5 is a diagrammatic cross-section of a conductor in accordance with the invention; and

Figure 6 is a diagrammatic cross-section of a cable in accordance with the invention.

Figure 1 shows a simple form of conductor in accordance with the invention, comprising a copper channel section 1 of rectangular overall shape within which is loosely housed a bundle 2 of elementary superconducting tapes 3 enclosed by an open helical wrapping 4 of polyimide (Kapton®) yarn or of polyaramid (Kevlar®) tape. The bundle is made captive within the copper section by a similar overall wrapping 5, but this allows the bundle freedom of movement of the order of 0.5mm in the direction of the width of the tape (horizontally parallel to the plane of the paper as drawn) The resilience and relatively low tension of the wrapping 4 also allows comparable relative movements between the individual elementary superconductors in the same direction. There is no substantial freedom of movement in other directions.

Although, for purposes of simple illustration, only four tapes are shown, larger numbers are contemplated.

In first and second modifications (not illustrated separately) the wrapping 4 and/or the wrapping 5 respectively is replaced with a thin flexible copper tape, which may if desired be wide enough to enclose completely the bundle or the bundle and the copper section, as the case may be; if so, there is an option to apply the copper tape longitudinally instead of helically.

Figure 2 illustrates a number of modifications that may be adopted independently; first, the tapes 3 are positioned vertically rather than horizontally in the copper section 1 (and are shown without the optional bundling tape); second, the open side of the copper channel section 1 is closed by a copper strip 6 secured by seam-welding or spot-welding to form a closed hollow copper section (seamless closed hollow sections can also be used, but insertion of the tapes is difficult); and third, the side faces of the copper section are inclined to give it a trapezoid section and facilitate asembly into a closely fitting tubular overall conductor: note that the inner side faces 8 remain vertical to permit face-to-face contact with the tapes 3.

Figure 3 also shows a number of independently usable modifications: more than one bundle 2 of tapes has been used; the sides of the copper section have been formed with potentially interlocking formations 9 (a rib) and 10 (a groove) to allow the formation of a self-supporting tubular overall conductor; and the bottom surface 11 of the copper section has been concavely curved to conform to the intended smooth bore of such an overall conductor.

Figure 4 shows how a copper section 1, initially of the shape shown in dotted lines, may be deformed after insertion of the tapes 3 (for instance by rolling) to make them captive without using any other component.

Figure 5 shows an alternative way of securing the bundle 2 by using a separate copper closure member 12 which is initally curved but is flattened to enter grooves 13 in the main copper section 1. It also shows an alternative shape for the rib 9 and groove 10 and illustrates the fact that the curvature of surface 11 may be convex, so as to form part of the outer surface of a smooth tubular conductor.

Figure 6 is a diagrammatic cross-section of a complete cable in accordance with the invention. It comprises concentric overall tubular inner and outer conductors 14 and 15 repectively. The inner conductor 14 is helically laid on and supported by an open helix 16 of stainless steel and comprises thirty-two conductors 17 of the form shown in Figure 1, each conductor having a copper cross-section of $15mm^2$ and enclosing ten elementary silver-clad BSSCO superconductors each 3mm wide and 0.2mm thick and having on average individual critical current (I_c) values of about 10A at 77K and about 40A at 40K under self-field conditions in each case, corresponding to critical current density (J_c) values of about $8kA/cm^2$ and $32kA/cm^2$ respectively.

The inner conductor 14 is enclosed in a conductor screen 18 comprising three carbon-loaded papers and one duplex paper (comprising plies of carbon-loaded and insulating grades of paper laid and bonded together in the paper-making process, the carbon-loaded ply facing the carbon-loaded paper tapes), insulation 19 comprising thirty-four insulating paper tapes with an aggregate thickness of

5mm and a dielectric screen 20 comprising another duplex paper tape and one carbon-loaded paper tape, following the usual practice for impregnated-paper insulated cables.

The outer overall conductor 15 is helically applied directly over the dielectric screen and comprises thirty-two of the conductors shown in Figure 1 and described above (here referenced 21) and six empty copper carriers (evenly spaced around the circumference) to complete the layer while keeping the numbers of conductors and their dimensions the same in both tubular conductors) and is surrounded by an outer screen 22 of three carbon-loaded and one duplex paper and outer insulation 23 consisting of twenty insulating paper tapes again with an aggregate thickness of 5mm (individual paper tapes are thicker than in the first insulation layer).

The remaining outer part of the cable is conventional and comprises a corrugated copper sheath 24 surrounded by "superinsulation" 25 (thermal insulation based on metallised foils under vacuum), further concentric copper tubes 26 and 27 defining an outer coolant duct 28 (maintained by spacers, not shown), another layer of superinsulation 29 and an outer metal jacket 30.

The cable is to be cooled (for example) by helium gas entering the central coolant duct at a temperature of about 25K and warming to about 58K by the time it reaches the other end of the cable, from where it returns *via* the outer coolant duct 28 where it will warm further, at most to about 230K, before returning to the refrigeration plant for reuse.

A short length of model cable was made in accordance with Figure 6, except that no empty carriers were used in the outer conductor (so that the capacity of the outer conductor was greater than that of the inner one), the outer part (from sheath 24 outwards) was omitted and the whole immersed in a

large cryogenic vessel. Terminations were made (prior to immersion) by locally soldering the tapes together and to the copper carriers with an alloy of 95%In, 5%Ag. At an operating temperature of 31K, this model cable was found capable of sustaining a supercurrent in excess of 10kA dc in its own self-field.

CLAIMS

1 A conductor for a superconducting cable comprising a hollow copper section having at least one elementary superconductor tape loosely housed within it so as to admit relative movement with respect to the copper section at least in the direction of the width of the tape.

2 A conductor as claimed in claim 1 in which, when terminated, substantial relative movement is permitted only in the said direction.

3 A conductor as claimed in claim 1 or claim 2 in which the hollow copper section extends around at least three sides of the tape or all of the tapes.

4 A conductor as claimed in claim 3 in which the copper section, having initially been open, is wholly or partly closed either by changing its shape or by adding a separate closure member after assembly with the tapes.

5 A conductor as claimed in any one of claims 1-4 in which the copper section has at least one flat internal surface presented to one of the flat faces of said tape (or one of said tapes) to provide opportunity for face-to-face contact.

6 A conductor as claimed in any one of claims 1-5 which is externally of a shape that can be assembled with identical or correspondingly shaped conductors, longitudinally or with a helical lay, to form a tubular overall conductor.

7 A conductor as claimed in claim 6 having interlocking formations on the surfaces of the copper sections that will be contiguous when so assembled.

8 A conductor as claimed in any one of claims 1-7 in which the said tape comprises a ceramic superconductor material.

9 A conductor as claimed in any one of claims 1-7 in which the said tape comprises a superconductor material of

empirical formula $Bi_{2-x}Pb_xSr_2Ca_2Cu_3O_{10-\delta}$ (where δ is less than 1).

10 A conductor as claimed claim 8 or claim 9 in which the tapes have been formed by a "powder-in-tube" process in which a silver tube is packed with the superconducting material (or a precursor that can be rendered superconducting by subsequent heat-treatment) and the tube then converted to a tape of much smaller cross-section by a process comprising at least one of drawing, swaging, rolling (longitudinal or transverse), rotary forging, or progressive pressing.

11 A conductor for a superconducting cable substantially as described by way of example with reference to one or more of Figures 1-5.

12 A superconducting cable comprising at least two conductors as claimed in any one of claims 1-11 and means for insulating them electrically from each other and thermally from the environment.

13 A cable as claimed in claim 12 including a plurality of said conductors asssembled to form at least two overall tubular conductors which are concentrically arranged around a central coolant duct.

14 A superconducting cable substantially as described with reference to Figure 6.

15 A superconducting cable installation comprising at least one cable as claimed in any one of claims 1-14 and means for cooling at least the conductors to a cryogenic working temperature.

Fig.1.

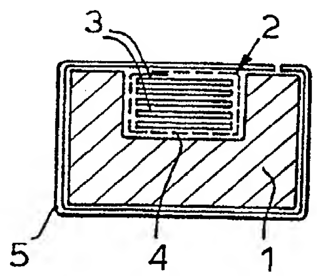


Fig.2.

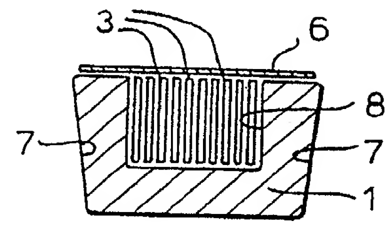


Fig.3.

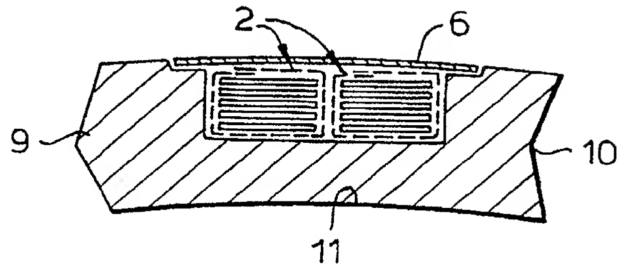


Fig.4.

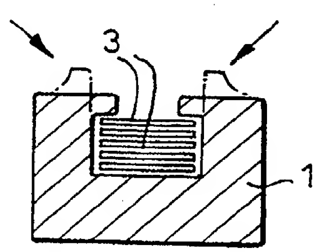


Fig.5.

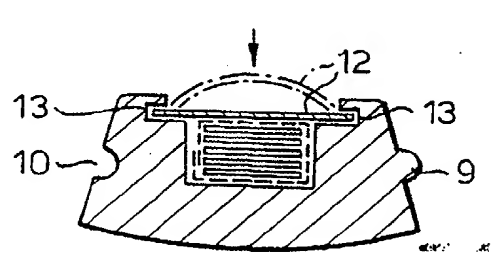
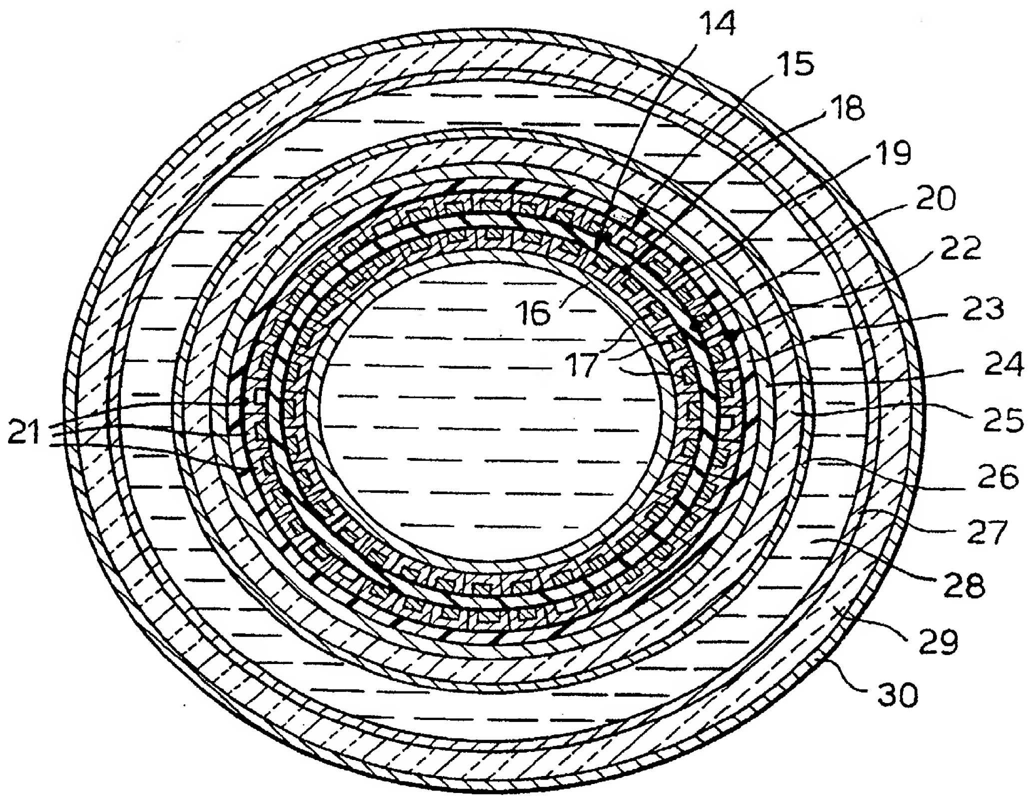


Fig.6.



INTERNATIONAL SEARCH REPORT

Interr ial Application No
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A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01B12/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP,A,0 451 864 (SUMITOMO ELECTRIC INDUSTRIES) 16 October 1991 see claims 1-13; figures 4-6 ---	1,15
A	PATENT ABSTRACTS OF JAPAN vol. 17, no. 371 (E-1396), 13 July 1993 & JP,A,50 062536 (HITACHI CABLE), 12 March 1993, see abstract -----	1,3-6

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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INTERNATIONAL SEARCH REPORT

Information on patent family members

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP-A-451864	16-10-91	DE-D- 69107230	23-03-95
		DE-T- 69107230	06-07-95
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		US-A- 5276281	04-01-94